AUTOCAPTURE PACING/SENSING CONFIGURATION

The present application is a Continuation-In-Part of co-pending applications Serial No. 09/206,329 filed on December 8, 1998, and entitled AUTOCAPTURE PACING/SENSING CONFIGURATION and Serial No. 09/206,896 filed on December 8,

5   1998 and entitled AUTOCAPTURE DETERMINATION FOR AN IMPLANTABLE CARDIOVERTER DEFIBRILLATOR.

I.   Field of the Invention

The present invention relates to cardiac rhythm management devices and, more

10   particularly, to an apparatus and method that automatically detects whether or not an electrical stimulus results in heart capture or contraction.

II.   Background of the Invention

Cardiac pacers have enjoyed widespread use and popularity through time as a

15   means for supplanting some or all of an abnormal heart's natural pacing functions. The various heart abnormalities remedied by pacemakers include total or partial heart block, arrhythmias, myocardial infarctions, congestive heart failure, congenital heart disorders, and various other rhythm disturbances within the heart. The general components of a cardiac pacemaker include an electronic pulse generator for generating stimulus pulses to

20   the heart coupled to an electrode lead arrangement (unipolar or bipolar) positioned adjacent or within a preselected heart chamber for delivering pacing stimulus pulses.

Regardless of the type of cardiac pacemaker employed to restore the heart's natural rhythm (ie: ventricular pacing, atrial pacing, or dual chamber pacing in both the atrium and ventricle), each type operates to stimulate excitable heart tissue cells adjacent to the

25   electrode of the pacing lead employed with the pacemaker, which may or may not result in capture. Myocardial response to stimulation or "capture" is a function of the positive and negative charges found in each myocardial cell within the heart. More specifically, the selective permeability of each myocardial cell works to retain potassium and exclude sodium such that, when the cell is at rest, the concentration of sodium ions outside of the

30   cell membrane is significantly greater than the concentration of sodium ions inside the cell membrane, while the concentration of potassium ions outside the cell membrane is

significantly less than the concentration of potassium ions inside the cell membrane. The selective permeability of each myocardial cell also retains other negative particles within the cell membrane such that the inside of the cell membrane is negatively charged with respect to the outside when the cell is at rest. When a stimulus is applied to the cell

5   membrane, the selective permeability of the cell membrane is disturbed and it can no longer block the inflow of sodium ions from outside the cell membrane. The inflow of sodium ions at the stimulation site causes the adjacent portions of the cell membrane to lose its selective permeability, thereby causing a chain reaction across the cell membrane until the cell interior is flooded with sodium ions. This process, referred to as

10   depolarization, causes the myocardial cell to have a net positive charge due to the inflow of sodium ions. The electrical depolarization of the cell interior causes a mechanical contraction or shortening of the myofibril of the cell. The syncytial structure of the myocardium typically causes the depolarization originating in any one cell to radiate through the entire mass of the heart muscle so that all cells are stimulated for effective

15   pumping. Following heart contraction or systole, the selective permeability of the cell membrane returns and sodium is pumped out until the cell is re-polarized with a negative charge within the cell membrane. This causes the cell membrane to relax and return to the fully extended state, referred to as diastole.

        In a normal heart, the sino-atrial (SA) node initiates the myocardial stimulation of

20   the atrium. The SA node comprises a bundle of unique cells disposed within the roof of the right atrium. Each cell membrane of the SA node has a characteristic tendency to leak ions gradually over time such that the cell membrane periodically breaks down and allows an inflow of sodium ions, thereby causing the SA node cells to depolarize. The SA node cells are in communication with the surrounding atrial muscle cells such that the

25   depolarization of the SA node cells causes the adjacent atrial muscle cells to depolarize. This results in atrial systole wherein the atria contract to empty blood into the ventricles. The atrial depolarization from the SA node is detected by the atrioventricular (AV) node which, in turn, communicates the depolarization impulse into the ventricles via the Bundle of His and Purkinje fibers following a brief conduction delay. In this fashion, ventricular

30   systole lags behind atrial systole such that the blood from the ventricles pumps through the body and lungs after being filled by the atria. Atrial and ventricular diastole follow,

wherein the myocardium is re-polarized and the heart muscle relaxed in preparation for the next cardiac cycle. It is when this system fails or functions abnormally that a cardiac pacer may be needed to deliver an electronic pacing stimulus for selectively depolarizing the myocardium of the heart so as to maintain proper heart rate and synchronization of the

5   filling and contraction of the atrial and ventricular chambers of the heart.

The success of a pacing stimulus in depolarizing or "capturing" the selected chamber of the heart hinges on whether the current of the pacing stimulus as delivered to the myocardium exceeds a threshold value. This threshold value, referred to as the capture threshold, is related to the electrical field intensity required to alter the permeability of the

10   myocardial cells to thereby initiate cell depolarization. If the local electrical field associated with the pacing stimulus does not exceed the capture threshold, then the permeability of the myocardial cells will not be altered enough and thus no depolarization will result. If, on the other hand, the local electrical field associated with the pacing stimulus exceeds the capture threshold, then the permeability of the myocardial cells will

15   be altered sufficiently such that depolarization will result.

Changes in the capture threshold may be detected by monitoring the efficacy of stimulating pulses at a given energy level. If capture does not occur at a particular stimulation energy level which previously was adequate to effect capture, then it can be surmised that the capture threshold has increased and that the stimulation energy should be

20   increased. On the other hand, if capture occurs consistently at a particular stimulation energy level over a relatively large number of successive stimulation cycles, then it is possible that the capture threshold has decreased such that the stimulation energy is being delivered at level higher than necessary to effect capture.

The ability of a pacemaker to detect capture is desirable in that delivering

25   stimulation pulses having energy far in excess of the patient's capture threshold is wasteful of the pacemaker's limited power supply. In order to minimize current drain on the power supply, it is desirable to automatically adjust the pacemaker such that the amount of stimulation energy delivered to the myocardium is maintained at the lowest level that will reliably capture the heart. To accomplish this, a process known as "capture verification"

30   must be performed wherein the pacemaker monitors to determine whether an evoked depolarization occurs in the preselected heart chamber following the delivery of each

pacing stimulus pulse to the preselected chamber of the heart.

The conventional pacemaker typically includes a pacing output circuit designed to selectively generate and deliver stimulus pulses through a lead to one or more electrodes positioned in the heart of a patient. While the conventional pacing circuit is generally

5 effective in delivering stimulus pulses to a selected chamber of the heart, it has been found that the detection of evoked depolarization or "capture verification" using the same electrode for pacing and sensing is difficult due to polarization voltages or "afterpotentials" which develop at the tissue/electrode interface following the application of the stimulation pulses. The ability to verify capture is further affected by other

10 variables including patient activity, body position, drugs being used, lead movement, noise etc.

Hence, a need exists for a cardiac pacing system having an autocapture pacing/sensing configuration that effectively avoids the affects of afterpotentials or that attenuates polarization voltages or "afterpotentials" which develop at the heart

15 tissue/electrode interface following the delivery of a stimulus to the heart tissue, and which minimizes the number of required components of the cardiac pacing system.

The present invention meets these needs and provides additional improvements and advantages that will be recognized by those skilled in the art upon review of the specification and figures.

20

SUMMARY OF THE INVENTION

The present invention provides an autocapture stimulation/sensing configuration for a cardiac electrical stimulation system. The system may be configured for sensing in either, both or between the atrium and ventricle of the heart. The system may include

25 either or both of an atrial lead and a ventricular lead. The atrial lead having one or more atrial electrodes electrically and the ventricular lead having one or more ventricular electrodes electrically. The atrial lead's electrodes may include atrial tip electrodes and/or atrial ring electrodes. The ventricular lead's electrodes may include ventricular tip electrodes, ventricular superior vena cava electrodes, ventricular coil electrodes, and/or

30 ventricular ring electrodes. The system may also include a left ventricular lead. The left ventricular lead may include one or more of a left ventricular ring electrode, a left

ventricular tip electrode, a coronary sinus ring electrode, a coronary sinus tip electrode and a coronary sinus coil. Further, the system may include an indifferent electrode and/or a can electrode. The system also includes a pulse generator. The pulse generator is typically enclosed in a housing. The pulse generator is electrically coupled to one or more

5   of the atrial electrodes and/or ventricular electrodes to provide an electrical stimulus to the atrium and/or ventricle of a heart. The system further includes one or more sensing circuits at least one of the sensing circuits configured to sense an evoked response. The evoked response sensing circuit senses an evoked response to the electrical stimulus from the pulse generator. The evoked response sensing circuit electrically is coupled to the

10   atrial electrodes and/or the ventricular electrodes to sense the evoked response. The evoked response sensing circuit is typically configured to sense the evoked response between and the pulse generator is typically configured to provide an electrical stimulus between one or more of the atrial ring electrode to the indifferent electrode, the atrial ring electrode to the ventricular tip electrode, the atrial ring electrode to the ventricular ring

15   electrode, the atrial ring electrode to the can electrode, the atrial ring electrode to the ventricle coil electrode, the atrial ring electrode to the superior vena cava coil electrode, the atrial tip electrode to the ventricular coil electrode, the atrial tip electrode to the ventricular ring electrode, the atrial tip electrode to the ventricular tip electrode, the atrial tip electrode to the indifferent electrode, the atrial tip electrode to the can electrode, the

20   atrial tip electrode to the atrial ring electrode, the superior vena cava coil electrode to the indifferent electrode, the superior vena cava coil electrode to the can electrode, the superior vena cava coil electrode to the atrial tip electrode, the superior vena cava coil electrode to the ventricular coil electrode, the superior vena cava coil electrode to the ventricular tip electrode, the ventricular coil electrode to the can electrode, the ventricular

25   coil electrode to the indifferent electrode, the ventricular ring electrode to the indifferent electrode, the ventricular ring electrode to the ventricular tip electrode, the ventricular tip electrode to the indifferent electrode, the ventricular tip electrode to the can electrode, the ventricular tip electrode to the ventricular coil electrode, the superior vena cava coil electrode to the ventricular ring electrode, the ventricular ring electrode to the can

30   electrode, and the ventricular ring electrode to the ventricular coil electrode.

A system in accordance with the present invention does not require an attenuation

means if the pacing and sensing electrodes are independent, although the system may include an afterpotential attenuation means to attenuate afterpotentials. Afterpotentials result from the application of the pacing stimulus to the heart by said cardiac pacing system. The afterpotential attenuation means is electrically coupled to the stimulation

5   means. Suitable afterpotential attenuating means are described in greater detail in co-pending applications serial number 09/070,158, filed April 30, 1998, 09/088,864, filed June 2, 1998, and 08/977,272, filed November 24, 1997, each of which have been assigned to the same assignee as the present application, the entire disclosures of which are incorporated herein by reference for any purpose.

10   The method in accordance with the present invention automatically determines whether or not an electrical stimulus evokes a response in the heart. The method utilizes a cardiac electrical stimulation system to apply the electrical stimulus. The system typically includes a pulse generator and an evoked response sensing circuit attached to atrial and/or ventricular leads configured as described above. An electrical stimulus is provided to at

15   least one of an atrium or ventricle of a heart. A signal indicative of the evoked response by the heart to the electrical stimulus is then sensed. The signal associated with an evoked response is typically sensed between at least one of the atrial electrodes and the ventricular electrodes.

        The present invention may be utilized with unipolar or bipolar atrial and

20   ventricular pacing and sensing leads, and which may attenuate and shorten afterpotentials and thereby enhance the detection of an evoked response in a preselected chamber of the heart. When used with atrial autocapture verification or evoked response detection, a bipolar atrial lead is preferred and the ventricular lead may be either unipolar or bipolar. Likewise, when used with ventricular autocapture, the ventricular lead is preferably

25   bipolar and the atrial lead can be either unipolar or bipolar. The present invention may utilize the pacing electrodes of a bipolar atrial lead and bipolar ventricular lead to both pace and sense an evoked response in a preselected chamber of the heart. The pacing system of the present invention may reduce the required blanking period and attenuate afterpotential developed at the pacing electrodes.

30   These and other objects and advantages of the present invention will be readily apparent to those skilled in the art from a review of the following detailed description of

the preferred embodiment in conjunction with the accompanying claims and drawings in which like numerals in the several views refer to corresponding parts.

BRIEF DESCRIPTION OF THE DRAWINGS

5   Figure 1 illustrates a cardiac pacing system in accordance with the present invention;

Figure 2 illustrates a cardiac pacing/defibrillation system in accordance with the present invention

Figure 3 is a schematic diagram of a portion of the cardiac pacing system's

10   pacing/sensing circuitry in accordance with the present invention;

Figure 4 is a schematic diagram of an alternate embodiment of a portion of the cardiac pacing system's pacing/sensing circuitry in accordance with the present invention;

Figure 5 is a schematic diagram of an alternate embodiment of a portion of the cardiac pacing system's pacing/sensing circuitry in accordance with the present invention;

15   Figure 6 is a schematic diagram of an alternate embodiment of a portion of the cardiac pacing system's pacing/sensing circuitry in accordance with the present invention;

Figure 7 is a schematic diagram of an alternate embodiment of a portion of the cardiac pacing system's pacing/sensing circuit of the present invention;

Figure 8 is a schematic diagram of an alternate embodiment of the pacing output

20   circuit of the present invention;

Figure 9 depicts a resulting pacing waveform observable between the ring and tip of a pacing lead positioned within the heart of a patient, when utilizing a conventional pacing circuit;

Figure 10 depicts a resulting pacing waveform observable between the ring and tip

25   of a pacing lead positioned within the heart of a patient, when utilizing the afterpotential attenuation means of the present invention;

Figure 11 depicts waveforms resulting from an atrial pacing stimulus and a ventricular pacing stimulus, wherein a first waveform is sensed with the atrial ring electrode and atrial tip electrode of the atrial pacing lead and a second waveform shown

30   for comparison is sensed with a surface ECG, while utilizing a conventional coupling capacitor, and wherein the pacing output or stimulus is below the required threshold

output;

Figure 12 depicts waveforms resulting from an atrial pacing output or stimulus, wherein the first waveform is sensed with the atrial ring electrode and atrial tip electrode of the atrial pacing lead and a second waveform shown for comparison is sensed with a surface ECG, while utilizing a conventional coupling capacitor, and wherein the pacing output is above the required threshold output;

Figure 13 depicts waveforms resulting from an atrial pacing output and a ventricular pacing output, wherein the first waveform is sensed with the atrial ring electrode and atrial tip electrode of the atrial pacing lead and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention, and wherein the pacing output is below the required threshold output;

Figure 14 depicts waveforms resulting from an atrial pacing output and a ventricular pacing output, wherein the first waveform is sensed with the atrial ring electrode and atrial tip electrode of the atrial pacing lead and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention, and wherein the pacing output is above the required threshold output;

Figure 15 depicts waveforms resulting from an atrial pacing output, wherein the first waveform is sensed with the atrial ring electrode and an indifferent electrode, and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention, and wherein the pacing output is below the required threshold output;

Figure 16 depicts waveforms resulting from an atrial pacing output, wherein the first waveform is sensed with the atrial ring electrode and an indifferent electrode, and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention, and wherein the pacing output is above the required threshold output;

Figure 17 depicts waveforms resulting from an atrial pacing output, wherein the first waveform is sensed with the atrial ring electrode and ventricular tip electrode, and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the

afterpotential attenuation means of the present invention, and wherein the pacing output is below the required threshold output;

Figure 18 depicts waveforms resulting from an atrial pacing output, wherein the first waveform is sensed with the atrial ring electrode and ventricular tip electrode, and a second waveform shown for comparison is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention, and wherein the pacing output is above the required threshold output and;

Figure 19 depicts waveforms resulting from an atrial pacing stimulus and a ventricular pacing stimulus, wherein a first waveform is sensed with a superior vena cava ventricular lead electrode and an indifferent electrode, the second or lower waveform is sensed with a ventricular coil electrode and an atrial ring electrode, and the third or upper waveform, shown for comparison, is sensed with a surface ECG, while utilizing the afterpotential attenuation means of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 1 illustrates a cardiac pacing system in accordance with the present invention. The cardiac pacing system includes a cardiac pacer 10, an atrial lead 12 and a right ventricular lead 14. In addition or as an alternative to right ventricular lead 14, the cardiac pacing system may include a left ventricular lead 80. The cardiac pacer 10 includes a header 16 and can 18, wherein a pulse generator 20 including pacing and sensing circuits 22 are contained therein. An indifferent electrode 24 of suitable known construction is positioned on the can 18 such that the indifferent electrode 24 is electrically isolated from the can 18 and is electrically coupled to the sensing circuit 22. Atrial lead 12, right ventricular lead 14 and left ventricular lead 80are engaged to header 16 and may be electrically coupled to the pulse generator 20 and pacing and sensing circuits 22 in a known suitable fashion. The atrial lead 12 is positioned in the atrium of the heart 26, wherein the atrial lead 12 includes a tip electrode 28 and ring electrode 30. The right ventricular lead 14 is positioned within the right ventricle of the heart 26, wherein the ventricular lead 14 includes a tip electrode 32 and ring electrode 34. The left ventricular lead 80 is positioned within the left ventricle of the heart 26, wherein the left ventricular lead 80 includes a tip electrode 84 and ring electrode 82.

Figure 2 illustrates a cardiac pacing/defibrillating system in accordance with the present invention. The cardiac pacing/defibrillating system includes an implantable cardioverter defibrillator 11, atrial lead 12 and ventricular lead 14. In addition or alternatively, the pacing defibrillation system may include a coronary sinus lead. The

5 implantable cardioverter defibrillator 11 includes a header 16 and can 18, wherein a pulse generator 20 including pacing and sensing circuits 22 and defibrillator circuit 24 are contained therein. An indifferent electrode 26 of suitable known construction is positioned on the can 18 such that the indifferent electrode 24 is electrically isolated from the can 18 and is electrically coupled to the sensing circuit 22. Atrial lead 12, ventricular

10 lead 14 and coronary sinus lead 15 are engaged to header 16 and may be electrically coupled to the pulse generator 20, pacing and sensing circuit 22, and defibrillator circuit 23 in a known suitable fashion. The atrial lead 12 is positioned in the atrium of the heart 26, wherein the atrial lead 12 includes a tip electrode 28 and ring electrode 30. The ventricular lead 14 is positioned through the superior vena cava with the distal portion

15 positioned within the ventricle of the heart 26. The ventricular lead 14 may include a tip electrode 32 and ventricular coil electrode 33 and superior vena cava coil electrode 35. Those skilled in the art will appreciate that the ventricular lead 14 may be utilized both for ventricular pacing and as a defibrillator lead, wherein the cardioverter defibrillator 11 is of the conventional type having modification to the pacing sensing circuit 22 as described

20 below in greater detail. The coronary sinus lead 15 is positioned through the coronary sinus with the distal portion positioned within the coronary artery of heart 26. The coronary sinus lead 15 may include a coronary sinus tip electrode 17, a coronary sinus ring electrode 19 and a coronary sinus coil 21.

Figure 3 illustrates a portion of the pacing and sensing circuit 22 combining the

25 electrode elements of cardiac pacer 10 and implantable cardioverter defibrillator 11. The circuit 22 includes an atrial intrinsic sense amplifier 36 electrically coupled between the atrial ring 30 and atrial tip 28. The circuit 22 also includes a ventricular intrinsic sense amplifier 38 electrically coupled between the ventricular ring electrode 34 and the ventricular tip electrode 32. A separate evoked response sense amplifier 40 is shown

30 electrically coupled to a multi-switch 42, wherein the evoked response sense amplifier 40 may be electrically coupled to sense evoked response waveforms resulting from either an

atrial pacing stimulus or ventricular pacing stimulus with any of the following sensing configurations: the atrial ring electrode to the indifferent electrode, the atrial ring electrode to the ventricular tip electrode, the atrial ring electrode to the ventricular ring electrode, the atrial ring electrode to the can, the atrial ring electrode to the ventricle coil, the atrial ring

5   electrode to the superior vena cava coil, the atrial tip electrode to the ventricular coil, the atrial tip electrode to the ventricular ring electrode, the atrial tip electrode to the ventricular tip electrode, the atrial tip electrode to the indifferent electrode, the atrial tip electrode to the can, the atrial tip electrode to the atrial ring electrode, the superior vena cava coil to the indifferent electrode, the superior vena cava coil to the can, the superior vena cava coil to

10   the atrial tip electrode, the superior vena cava coil to the ventricular coil electrode, the superior vena cava coil to the ventricular tip electrode, the ventricular coil to the can, the ventricular coil to the indifferent electrode, the ventricular ring electrode to the indifferent electrode, the ventricular ring electrode to the ventricular tip electrode, the ventricular tip electrode to the indifferent electrode, the ventricular tip electrode to the can, the

15   ventricular tip electrode to the ventricular coil, the superior vena cava coil to the ventricular ring electrode, the ventricular ring electrode to the can, and the ventricular ring electrode to the ventricular coil. Those skilled in the art will appreciate that the preferred sensing configuration utilizing the separate evoked response sense amplifier 40 will vary depending upon whether the pacing stimulus is unipolar or bipolar and whether the pacing

20   stimulus is directed in the atrium or ventricle. Those skilled in the art will appreciate that the sensing configuration may utilize a second evoked response amplifier 40. The use of a second evoked response amplifier 40 typically depends on whether the pacing stimulus is unipolar or bipolar and whether the pacing stimulus is directed to the atrium or ventricle.

When unipolar pacing in the ventricle, the ventricle evoked response may be

25   sensed without the need for an attenuation means by sensing between the atrial ring electrode to the atrial tip electrode, the superior vena cava coil to the atrial tip electrode, the superior vena cava coil to the atrial ring electrode, the ventricular ring electrode to the atrial ring electrode, the ventricular ring electrode to the superior vena cava coil, the right ventricular coil to the atrial tip electrode, the right ventricular coil to the atrial ring

30   electrode, the right ventricular coil to the superior vena cava coil, the indifferent electrode to the atrial tip electrode, the indifferent electrode to the atrial ring electrode, the

indifferent electrode to the superior vena cava coil, and the indifferent electrode to the right ventricular coil. Alternatively, the ventricular evoked response from unipolar pacing may be sensed with an attenuation means by sensing between the ventricular tip electrode to the atrial tip electrode, the ventricular tip electrode to the atrial ring electrode, the

5   ventricular tip electrode to the superior vena cava coil, the right ventricular coil to the ventricular tip electrode, the can to the atrial tip electrode, the can to the atrial ring electrode, the can to the superior vena cava coil, the can to the ventricular tip electrode, the can to the ventricular ring electrode, the can to the right ventricular coil, and the indifferent electrode to the can.

10   In addition, when unipolar pacing in the left ventricle, the left ventricular evoked response may also be sensed without the need for an attenuation means by sensing between the atrial tip electrode to the left ventricular ring electrode, the atrial ring electrode to the left ventricular ring electrode, the superior vena cava coil to the left ventricular ring electrode, the right ventricular tip electrode to the left ventricular ring

15   electrode, the right ventricular ring electrode to the left ventricular ring electrode, the right ventricular coil to the left ventricular ring electrode, the can to the left ventricular ring electrode, the indifferent electrode to the left ventricular ring electrode, the atrial tip electrode to the coronary sinus ring electrode, the atrial ring electrode to the coronary sinus ring electrode, the superior vena cava coil to the coronary sinus ring electrode, the right

20   ventricular tip electrode to the coronary sinus ring electrode, the right ventricular ring electrode to the coronary sinus ring electrode, the right ventricular coil to the coronary sinus ring electrode, the can to the coronary sinus ring electrode, the indifferent electrode to the coronary sinus ring electrode, the left ventricular ring electrode to the coronary sinus ring electrode, the atrial tip electrode to the coronary sinus tip electrode, the atrial ring

25   electrode to the coronary sinus tip electrode, the superior vena cava coil to the coronary sinus tip electrode, the right ventricular tip electrode to the coronary sinus tip electrode, the right ventricular ring electrode to the coronary sinus tip electrode, the right ventricular coil to the coronary sinus tip electrode, the can to the coronary sinus tip electrode, the indifferent electrode to the coronary sinus tip electrode, the left ventricular ring electrode

30   to the coronary sinus tip electrode, the coronary sinus ring electrode to the coronary sinus tip electrode, the atrial tip electrode to the coronary sinus coil, the atrial ring electrode to

the coronary sinus coil, the superior vena cava coil to the coronary sinus coil, the right ventricular tip electrode to the coronary sinus coil, the right ventricular ring electrode to the coronary sinus coil, the right ventricular coil to the coronary sinus coil, the can to coronary sinus coil, the indifferent electrode to the coronary sinus coil, the left ventricular ring electrode to the coronary sinus coil, the coronary sinus ring electrode to the coronary sinus coil, and the coronary sinus tip electrode to the coronary sinus coil. Alternatively, the left ventricular evoked response from unipolar pacing may also be sensed with an attenuation means by sensing between the atrial tip electrode to the left ventricular tip electrode, the atrial ring electrode to the left ventricular tip electrode, the superior vena cava coil to the left ventricular tip electrode, the right ventricular tip electrode to the left ventricular tip electrode, the right ventricular ring electrode to the left ventricular tip electrode, the right ventricular coil to the left ventricular tip electrode, the can to the left ventricular tip electrode, the indifferent electrode to the left ventricular tip electrode, the left ventricular ring electrode to the left ventricular tip electrode, the left ventricular tip electrode to the coronary sinus ring electrode, the left ventricular tip electrode to the coronary sinus tip electrode and the left ventricular tip electrode to the coronary sinus coil.

When bipolar pacing in the ventricle, the ventricular evoked response may be sensed without the need for an attenuation means by sensing between the atrial ring electrode to the atrial tip electrode, the superior vena cava coil to the atrial tip electrode, the superior vena cava coil to the atrial ring electrode, the can to the atrial tip electrode, the can to the atrial ring electrode, the can to the superior vena cava coil, the indifferent electrode to the atrial tip electrode, the indifferent electrode to the atrial ring electrode, and the indifferent electrode to the superior vena cava coil. Alternatively, the ventricular evoked response from bipolar pacing may be sensed with an attenuation means by sensing between the ventricular tip electrode to the atrial tip electrode, the ventricular tip electrode to the atrial ring electrode, the ventricular tip electrode to the superior vena cava coil, the ventricular ring electrode to the ventricular tip electrode, the right ventricular coil to the ventricular tip electrode, the superior vena cava coil to the ventricular ring electrode, the superior vena cava coil to the right ventricular coil, the atrial ring electrode to the ventricular ring electrode, the atrial ring electrode to the right ventricular coil, the atrial tip electrode to the ventricular ring electrode, the atrial tip electrode to the right ventricular

coil, the can to the ventricular tip electrode, the can to the ventricular ring electrode, the can to the right ventricular coil, the indifferent electrode to the ventricular tip electrode, the indifferent electrode to the ventricular ring electrode, the indifferent electrode to the right ventricular coil, and the indifferent electrode to the can.

5   In addition, when bipolar pacing in the left ventricle, the left ventricular evoked response may also be sensed without the need for an attenuation means by sensing between the atrial tip electrode to the coronary sinus ring electrode, the atrial tip electrode to the coronary sinus tip electrode, the atrial tip electrode to the coronary sinus coil, the atrial ring electrode to the coronary sinus ring electrode, the atrial ring electrode to the

10   coronary sinus tip electrode, the atrial ring electrode to the coronary sinus coil, the superior vena cava coil or the coronary sinus ring electrode, the superior vena cava coil to the coronary sinus tip electrode, the superior vena cava coil to the coronary sinus coil, the can to the coronary sinus ring electrode, the can to the coronary sinus tip electrode, the can to the coronary sinus coil, the indifferent electrode to the coronary sinus ring electrode, the

15   indifferent electrode to the coronary sinus tip electrode, the indifferent electrode to the coronary sinus coil, the coronary sinus ring electrode to the coronary sinus tip electrode, the coronary sinus ring electrode to the coronary sinus coil, and the coronary sinus tip electrode to the coronary sinus coil. Alternatively, the left ventricular evoked response from bipolar pacing may also be sensed with an attenuation means by sensing between the

20   atrial tip electrode to the left ventricular ring electrode, the atrial tip electrode to the left ventricular tip electrode, the atrial ring electrode to the left ventricular ring electrode, the atrial ring electrode to the left ventricular tip electrode, the superior vena cava coil to the left ventricular ring electrode, the superior vena cava coil to the left ventricular tip electrode, the right ventricular tip electrode to the left ventricular ring electrode, the right

25   ventricular tip electrode to the left ventricular tip electrode, the right ventricular tip electrode to the coronary sinus ring electrode, the right ventricular tip electrode to the coronary sinus tip electrode, the right ventricular tip electrode to the coronary sinus coil, the right ventricular ring electrode to the left ventricular ring electrode, the right ventricular ring electrode to the left ventricular tip electrode, the right ventricular ring

30   electrode to the coronary sinus ring electrode, the right ventricular ring electrode to the coronary sinus tip electrode, the right ventricular ring electrode to the coronary sinus coil,

the right ventricular coil to the left ventricular ring electrode, the right ventricular coil to the left ventricular tip electrode, the right ventricular coil to the coronary sinus ring electrode, the right ventricular coil to the coronary sinus tip electrode, the right ventricular coil to the coronary sinus coil, the can to the left ventricular ring electrode, the can to the

5   left ventricular tip electrode, the indifferent electrode to the left ventricular ring electrode, the indifferent electrode to the left ventricular tip electrode, the left ventricular ring electrode to the left ventricular tip electrode, the left ventricular ring electrode to the coronary sinus ring electrode, the left ventricular ring electrode to the coronary sinus tip electrode, the left ventricular ring electrode to the coronary sinus coil, the left ventricular

10   tip electrode to the coronary sinus ring electrode, the left ventricular tip electrode to the coronary sinus tip electrode, and the left ventricular tip electrode to the coronary sinus coil.

        When unipolar pacing in the atrium, the atrial evoked response may be sensed without the need for an attenuation means by sensing between the atrial ring electrode to

15   the superior vena cava coil, the atrial ring electrode to the ventricular tip electrode, the superior vena cava coil to the ventricular tip electrode, the atrial ring electrode to the ventricular ring electrode, the atrial ring electrode to the right ventricular coil, the superior vena cava coil to the ventricular ring electrode, the superior vena cava coil to the right ventricular coil, the ventricular tip electrode to the ventricular ring electrode, the

20   ventricular tip electrode to the right ventricular coil, the superior vena cava coil to the indifferent electrode, the ventricular tip electrode to the indifferent electrode, the ventricular ring electrode to the indifferent electrode, and the right ventricular coil to the indifferent electrode. Alternatively, the atrial evoked response from unipolar pacing may be sensed with an attenuation means be sensing between the atrial tip electrode to the atrial

25   ring electrode, the atrial tip electrode to the superior vena cava coil, the atrial tip electrode to the ventricular tip electrode, the atrial tip electrode to the ventricular ring electrode, the atrial tip electrode to the right ventricular coil, the atrial tip electrode to the can, the atrial tip electrode to the indifferent electrode, the atrial ring electrode to the can, the superior vena cava coil to the can ventricular tip electrode to the can, the ventricular ring electrode

30   to the can, the right ventricular coil to the can, and the can to the indifferent electrode.

        When bipolar pacing in the atrium, the atrial evoked response may be sensed

without the need for an attenuation means by sensing between the superior vena cava coil
to the ventricular tip electrode, the superior vena cava coil to the ventricular ring electrode,
the superior vena cava coil to the right ventricular coil, the superior vena cava coil to the
can, the superior vena cava coil to the indifferent electrode, the ventricular tip electrode to

5   the ventricular ring electrode, the ventricular tip electrode to the right ventricular coil, the
ventricular tip electrode to the can, the ventricular tip electrode to the indifferent electrode,
the ventricular ring electrode to the can, the ventricular ring electrode to the indifferent
electrode, the right ventricular coil to the can, and the right ventricular coil to the
indifferent electrode. Alternatively, the atrial evoked response from bipolar pacing may be

10   sensed with an attenuation means by sensing between the atrial tip electrode to the atrial
ring electrode, the atrial tip electrode to the superior vena cava coil, the atrial tip electrode
to the ventricular tip electrode, the atrial tip electrode to the ventricular ring electrode, the
atrial tip electrode to the right ventricular coil, the atrial tip electrode to the can, the atrial
tip electrode to the indifferent electrode, the atrial ring electrode to the superior vena cava

15   coil, the atrial ring electrode to the ventricular tip electrode, the atrial ring electrode to the
ventricular ring electrode, the atrial ring electrode to the right ventricular coil, the atrial
ring electrode to the can, the atrial ring electrode to the indifferent electrode, and the can to
the indifferent electrode.

        Figures 4-6 illustrate alternative embodiments of a portion of the pacing/sensing

20   circuit 22 detailing the electrode elements of cardiac pacer 10 for exemplary purposes.
Figure 4 shows a dedicated atrial evoked response amplifier 40 electrically coupled
between the atrial ring electrode 30 and the ventricular tip electrode 32. Figure 5 shows an
alternate embodiment of a portion of the pacing and sensing circuit 22, wherein the
dedicated atrial evoked response amplifier 40 is electrically coupled between the atrial ring

25   electrode 30 and the indifferent electrode 24 and a dedicated ventricular evoked response
amplifier 44 is electrically coupled between the ventricular ring electrode 34 and the
ventricular tip electrode 32. Figure 6 shows an alternate embodiment of a portion of the
pacing and sensing circuit 22, wherein the dedicated atrial evoked response amplifier 40 is
electrically coupled between the indifferent electrode 24 and the ventricular tip electrode

30   32 and a dedicated ventricular evoked response amplifier 44 is electrically coupled
between the ventricular ring electrode 34 and the ventricular tip electrode 32.

The inventors have found that the affects of the pacing afterpotentials on the sensed evoked response during autocapture detection may be avoided when the pacing electrodes and the sensing electrodes are independent of one another. Therefore, the use of independent pacing and sensing electrodes in certain configurations eliminates the need for

5   an attenuation means for these configurations. Additionally, the pacing circuit of the present invention may be utilized when sensing an evoked response in accordance with the above configurations or when utilizing an electrode for both pacing and sensing in combination with an attenuation means.

Referring to Figure 7, a portion of the exemplary embodiment of the pacing and

10   sensing circuit 22 shown in Figure 4 is illustrated in greater detail. Those skilled in the art will appreciate that pacing/sensing circuit 22 may be modified slightly to achieve any of the above identified sensing configurations for atrial evoked response or any of the above identified sensing configurations for ventricular evoked response. Thus, the description of the pacing/sensing circuit as shown in Figure 4 should not be construed as limiting. As

15   will be explained below, the improved circuit 22 is capable of quickly attenuating any polarization voltages or "afterpotential" which result due to the application of stimulus pulses to the heart 26. By attenuating the polarization voltages or "afterpotential" in this fashion, the improved circuit 22 facilitates the task of capture verification in that the presence or absence of evoked responses may be readily determined without the masking

20   caused by afterpotential. Capture verification advantageously allows the pacemaker 10 to automatically adjust the pacing output parameters so as to minimize power consumption while assuring therapeutic efficacy.

In the exemplary embodiment shown in Figure 7, the circuit 22 includes a power supply or battery 46, a first switch (S1) 48, a second switch (S2) 50, a third switch (S3) 52,

25   a pacing charge storage capacitor (C1) 54, and an afterpotential reduction capacitor/coupling capacitor (C2) 56, all of which are cooperatively operable under the direction of a controller of known suitable construction. The power supply or battery 46 is preferably the battery provided to power the pacemaker 10 and may comprise any number of commercially available batteries suitable for pacing applications. The switches 48-52

30   are preferably carried out via any number of conventionally available microprocessor-directed semiconductor integrated circuit switching means. The pacing charge storage

capacitor 54 may also comprise any number of conventional storage capacitors, but is preferably provided with a capacitance in the range of 10-30 microfarads so as to develop a sufficient pacing charge for stimulating the heart 26. The primary function of the coupling capacitor 56 is to quickly attenuate the polarization voltage or "afterpotential"

5   which result from pacing and additionally block any DC signals from reaching the heart 26 during pacing. The coupling capacitor 56 has a capacitance in the range less than 5 microfarads, with a 2.2 microfarad capacitor being preferred.

The sensing portion of the circuit 22 includes pace blanking switches 58 and 60, passive filters 62 and 64, voltage reference 66, sense amplifier blanking switches 68 and

10   70, preamplifier 72, band pass filter 74, analog to digital converter 76 and detection comparator 78. The controller is operatively coupled to the circuit 22 and controls the opening and closing of switches 58, 60, 68, and 70. Although switches 58, 60, 68, and 70 are illustrated as discrete components, those skilled in the art will appreciate that they may comprise any number of commercially available microprocessor-directed semiconductor

15   integrated circuit switching means. The pace blanking switches 58 and 60 are closed independently to detect an evoked response from the corresponding pacing electrode, and the shortening of the pacing afterpotential by using a reduced capacitance coupling capacitor allows pacing and sensing of the evoked response from the same electrodes. The intrinsic sensing channel may also be shared for efficient system operation. By shortening

20   the pacing afterpotential, the recharge time of the coupling capacitor 56 may be reduced from a conventional time of greater than 20 milliseconds to under 10 milliseconds. This shortened time usually lapses before the onset of an evoked response. In turn, the sense amplifier blanking time may be reduced from a conventional 30 milliseconds to under 15 milliseconds with 12 milliseconds being preferred. This shortened blanking period in

25   conjunction with the shortening of the pacing afterpotential increases the likelihood of detecting an evoked response.

Having described the constructional features of the pacing and sensing circuit the mode of use will next be described in greater detail. The controller implements a pre-programmed sequence to control the charging cycle, pacing cycle, and recharge cycle of

30   the pacing output circuit. The charging cycle is characterized as having the first switch 48 in a closed state with the second switch 50 and third switch 52 in an open state. In this

configuration, the pacing charge storage capacitor 54 may be charged up to a predetermined pacing voltage level, such as 3 volts. After the pacing charge storage capacitor 54 has been charged up to the predetermined pacing voltage level, the pacing cycle then operates to deliver the pacing charge from the pacing charge storage capacitor

5   54 to the heart 26.

To accomplish the pacing cycle, the first switch 48 is opened and third switch 52 remains opened and the second switch 50 is closed. This allows the voltage within the pacing charge storage capacitor 54 to be discharged through the coupling capacitor 56 to the tip electrode 28 positioned in the heart 26. The coupling capacitor 56 is less than 5

10   microfarads. This, once again, effectively blocks any significant DC signals from reaching the heart 26, while shortening the pacing afterpotential. Those skilled in the art will appreciate that in those configurations where the pacing is between the tip electrode and the can and sensing is between an atrial lead electrode and ventricular lead electrode as described above, a coupling capacitor of known suitable construction may instead be

15   utilized.

The recharge cycle involves keeping open the first switch 48 and opening the second switch 50 while closing the third switch 52. This allows the circuit 22 to passively recharge, such that the charge within the heart 26 is allowed to flow back into the pacing output circuit to balance out. During this passive recharge period, the charge on the

20   coupling capacitor 56 is such that the signal decays over a short period of time and less than the required blanking period preceding detection of any evoked response from the heart 26. This is because the evoked responses from the heart 26 typically begins within 12 milliseconds from the delivery of a stimulus pulse to the atrium and within 20 milliseconds from the delivery of a stimulus pulse to the ventricle, which is substantially

25   longer than the required recharge time. Advantageously, it has been found that reducing the overall capacitance of the coupling capacitor 56 quickly attenuates the polarization voltages or "afterpotentials" which result immediately following the application of a stimulus pulse such that the evoked responses within the heart 26 will not be masked or buried within the "afterpotential." By eliminating the adverse affects of "afterpotential" in

30   this fashion, the pacemaker 10 can easily sense an evoked response and track the capture threshold of the heart 26 over time. Those skilled in the art will appreciate that with the

continuous evaluation of an evoked response, the pacemaker 10 may be automatically adjusted to maintain an optimal pacing stimulus level which ensures safe pacing while minimizing power consumption.

Referring now to Figure 8, a portion of the pacing and sensing output circuit 22 is

5   shown having a modified pacing circuit 80 for exemplary purposes, wherein the circuit 80 is capable of quickly attenuating polarization voltages or "afterpotential" which result due to the application of stimulus pulses to the heart 26. By attenuating the polarization voltages or "afterpotential" in this fashion, the improved pacing circuit 80 of the present invention facilitates the task of capture verification in that the presence or absence of

10   evoked responses may be readily determined without the masking caused by afterpotential. Capture verification may advantageously allow the pacemaker 10 to automatically adjust the capture threshold so as to minimize power consumption while assuring therapeutic efficacy.

The pacing output circuit 80 of the present invention includes a power supply or

15   battery 82, a first switch 84, a second switch 86, a third switch 88, a fourth switch 90, a pacing charge storage capacitor 92, a first coupling capacitor 94, and a second coupling capacitor 96, all of which are cooperatively operable under the direction of a controller. By way of example, the improved pacing output circuit 80 is illustrated in a ventricular pacing arrangement for delivering stimulus pulses to the heart 26 via the tip electrode 32

20   and ring electrode 34 of the ventricular pacing lead 14 shown in Figure 1. It is to be readily understood, however, that the improved pacing output circuit 80 of the present invention may also find application in an atrial pacing arrangement.

The power supply or battery 82 is preferably the battery provided to power the pacemaker 10 and may comprise any number of commercially available batteries suitable

25   for pacing applications. The switches 84-90 are illustrated as discrete components but are preferably carried out via any number of commercially available microprocessor-directed semiconductor integrated circuit switching means. The pacing charge storage capacitor 92 may also comprise any number of commercially available storage capacitors, but is preferably provided with a capacitance in the range greater than 10 microfarads so as to

30   develop a sufficient pacing charge for stimulating the heart 26.

One function of the second coupling capacitor 96 is to block DC signals from

reaching the heart 26 during pacing. In order to minimize the pacing pulse droop the second coupling capacitor 96 should have a sufficiently large capacitance, for example, greater than 10 microfarads. In an important aspect of the present invention, the first coupling capacitor 94 is advantageously provided having a capacitance preferably less

5   than 5 microfarads and substantially smaller than that of the second coupling capacitor 96. As will be described in greater detail below, the first coupling capacitor 94 may be selectively operable, via the fourth switch 90, so as to selectively reduce the effective capacitance of the second coupling capacitor 96, thereby quickly attenuating the polarization voltage or "afterpotential" which result from pacing.

10   Having described the constructional features of the modified pacing circuit 80, the operation of the pacing output circuit 80 will now be described. During a normal pacing mode, the pacing output circuit 80 engages in a charging cycle, a pacing cycle, and a recharge cycle. The charging cycle is characterized as having the first switch 84 in a closed state with the second and third switches 86-90 in an open state. In this configuration, the

15   pacing charge storage capacitor 92 may be charged up to a predetermined pacing voltage level, such as 3 volts. After the pacing charge storage capacitor 92 has been charged up to the predetermined pacing voltage level, the pacing cycle then operates to deliver the pacing charge from the pacing charge storage capacitor 92 to the heart 26. To accomplish this pacing cycle, the first switch 84 and third switch 88 are in the open state and the

20   second switch 86 and fourth switch 90 may be in the closed state. This allows the voltage within the pacing charge storage capacitor 92 to be discharged through the second coupling capacitor 96 to the tip electrode 32 of the pacemaker 10. Maintaining the fourth switch 90 in a closed state effectively bypasses the first coupling capacitor 94 such that the second coupling capacitor 96 is at its full capacitance level of approximately greater than

25   10 microfarads. This, once again, effectively blocks any DC signals from reaching the heart 26. In another alternate preferred embodiment, during the normal pacing mode, the fourth switch 90 may be open so long as the pacing threshold does not exceed a predetermined limit. In this manner detection of an evoked response (autocapture) may be enhanced during the normal pacing mode. During the autothreshold pacing mode, the

30   fourth switch 90 is always in the open state and is closed for normal pacing.

        The recharge cycle during normal pacing involves having the first switch 84 and

the second switch 86 in the open state, while having the third switch 88 in the closed state. This allows the circuit 80 to passively recharge, such that the charge within the heart 26 is allowed to flow back into the circuit 80 to balance out. As noted above, during this passive recharge period, the charge on the second coupling capacitor 96 may be such that

5   the afterpotential signal exponentially decays over a relatively long period of time lasting up to 100 milliseconds. This large "afterpotential" signal unwontedly masks out any evoked response from the heart 26. This is because the evoked responses from the heart 26 typically occur within 20 milliseconds from the delivery of the stimulus pulse to the ventricle and are substantially smaller in magnitude than the large "afterpotential" which

10   would develop within the second coupling capacitor 96, were it not for the present invention.

In one embodiment of the present invention, it is an important aspect of the present invention that the polarization voltages or "afterpotential" which result from pacing quickly attenuate. This is achieved by having fourth switch 90 in the open state such that

15   the first coupling capacitor 94 and second coupling capacitor 96 are connected in series. The series coupling of the first coupling capacitor 94 and second coupling capacitor 96 causes the overall capacitance to approximate the lower capacitance, or in other words, the capacitance of the first coupling capacitor 94. In a preferred embodiment, the first coupling capacitor 94 may be provided having a capacitance in the range of 1-2

20   microfarads such that, for a brief moment, the overall capacitance between the afterpotential reduction capacitor 94 and coupling capacitor 96 is approximately 1-2 microfarads. Advantageously, it has been found that reducing the effective capacitance of the second coupling capacitor 96 quickly attenuates the polarization voltages or "afterpotential" which result immediately following the application of a stimulus pulse

25   such that the evoked responses within the heart 26 will not be masked or buried within the "afterpotential." By eliminating the adverse affects of "afterpotential" in this fashion, the pacemaker 10 can easily determine and track the capture threshold of the heart 26 over time. Those skilled in the art will appreciate that with the continuous knowledge of the capture and pacing threshold in hand, the pacemaker 10 may be automatically adjusted to

30   maintain an optimal pacing stimulus level which ensures safe pacing while minimizing power consumption.

Referring next to Figures 9 and 10, the resulting pacing waveforms 150 and 152 detected with the tip and ring of a pacing lead, for the conventional pacing circuit and the pacing circuit of Figure 9 respectively, are shown for comparison. By electrical analysis theory, familiar to those skilled in the art, the pacing afterpotential signal decay

5   characteristics are determined by the time constant formed by the product of the coupling capacitor (blocking) and the load (a combination of the impedance of the lead body, electrode/tissue interface, and myocardium). When the capacitance of the coupling capacitor is reduced, the afterpotential has a larger initial amplitude but dissipates faster (compare afterpotential amplitudes 154 and 156 for the respective pacing afterpotential

10   waveforms 150 and 152). The blanking period 158 before sensing for the conventional capacitor is greater than the required blanking period 160 when utilizing a 1 microfarad coupling capacitor (see Figures 9 and 10 for comparison). Also, the recharge time 162 when utilizing a conventional coupling capacitor is significantly longer than the required recharge time 164 required for the 1 microfarad capacitor. Further, the recharge time 162

15   overlaps into sensing period 166 for the conventional capacitor, whereas the recharge time 164 terminates prior to the beginning of the sensing period 168 for the 1 microfarad capacitor. Hence, when the coupling capacitance is sufficiently small, for example, less than 5 microfarads, the pacing afterpotential will settle to baseline at a faster rate and before the onset of the evoked response, thereby making detection of the evoked response

20   feasible.

Those skilled in the art will appreciate that as the coupling capacitance decreases, the pacing pulse seen by the heart will bear a larger droop and the threshold voltage that evokes a response increases. Thus, if a small coupling capacitance is utilized during a determination of the threshold, the determined threshold will be greater than the actual

25   threshold required during normal pacing (assuming that a conventional coupling capacitance is utilized during normal pacing), thereby increasing the pacing safety margin.

Referring next to Figures 11 and 12, a recorded signal sensed between the atrial tip electrode 28 and the atrial ring electrode 30 resulting from a paced stimulus between the atrial tip electrode 28 and the atrial ring electrode 30 is shown, wherein a conventional

30   coupling capacitor was utilized in the pacing and sensing circuit 22. Figure 11 illustrates a resulting output or signal 178 and corresponding surface electrocardiogram (ECG) signal

180, wherein the pacing output voltage is below the known threshold. Figure 12 illustrates a resulting signal 182 and corresponding ECG signal 184, wherein the pacing output voltage is above the known threshold. Those skilled in the art will appreciate that the intra cardiac signals 178 and 182 are overwhelmed with pacing afterpotential and, thus, the

5   evoked response and non-captured artifacts during capture and non-capture respectively are not easily distinguishable within 100 milliseconds after pacing.

Figures 13 and 14 show recorded signals sensed between the atrial tip electrode 28 and the atrial ring electrode 30 resulting from a paced stimulus between the atrial tip electrode 28 and the atrial ring electrode 30 received when implementing a 2 microfarad

10   coupling capacitor having an 8 millisecond recharge time and a blanking time of 10 milliseconds. Figure 13 illustrates a resulting output or signal 186 and corresponding surface electrocardiogram (ECG) signal 188, wherein the pacing output voltage is below the known threshold. Figure 14 illustrates a resulting signal 190 and corresponding ECG signal 192, wherein the pacing output voltage is above the known threshold. The evoked

15   response and non-captured artifacts are readily distinguishable during capture and non-capture for signals 186 and 190. Without limitation, a conventional peak detector may be adapted for detecting the peaks in the recorded signal received after pacing while using a 1 microfarad coupling capacitor having a 8 millisecond recharge time.

Figures 15 and 16 show recorded signals sensed between the atrial ring electrode

20   30 and the indifferent electrode 24 resulting from a paced stimulus between the atrial ring electrode 30 and the can 18. The recorded signals were received while implementing a 2 microfarad coupling capacitor having a 10 millisecond recharge time and a blanking time of 12 milliseconds. Figure 15 illustrates a resulting output or signal 194 and corresponding surface electrocardiogram (ECG) signal 196, wherein the pacing output

25   voltage is below the known threshold. Figure 16 illustrates a resulting signal 198 and corresponding ECG signal 200, wherein the pacing output voltage is above the known threshold. The evoked response and non-captured artifacts are readily distinguishable during capture and non-capture for signals 194 and 198. As best seen in Figure 17, the evoked response is readily distinguishable from output associated with polarization.

30   Figures 17 and 18 show recorded signals sensed between the atrial ring electrode 30 and the ventricular tip electrode 32 resulting from a paced stimulus between the atrial

ring electrode 30 and the can 18. The recorded signals were received while implementing a 2 microfarad coupling capacitor having a 10 millisecond recharge time and a blanking time of 12 milliseconds. Figure 17 illustrates a resulting output or signal 202 and corresponding surface electrocardiogram (ECG) signal 204, wherein the pacing output

5   voltage is below the known threshold. Figure 18 illustrates a resulting signal 206 and corresponding ECG signal 208, wherein the pacing output voltage is above the known threshold. The evoked response and non-captured artifacts are readily distinguishable during capture and non-capture for signals 202 and 206. As discussed above, those skilled in the art will appreciate that noise is less likely to affect the recorded signal sensed

10   between the atrial ring electrode 30 and ventricular tip electrode 32 and further the sensing configuration may also be utilized to detect a ventricular evoked response.

Figure 19 illustrates the resulting waveforms 200, 202, and 204 from paced stimuli which were received when implementing a 2 microfarad coupling capacitor having an 8 millisecond recharge time and a blanking time of 10 milliseconds. The waveform 200 was

15   detected between the superior vena cava coil electrode and an indifferent electrode 26 positioned on the can 18. Waveform 202 was detected between the ventricular coil electrode and an atrial ring electrode. Waveform 204 was detected from a conventional surface electrocardiogram. The portion of waveforms 200 and 202 indicated as non-capture are the result of pacing stimulus below threshold. Those skilled in the art will

20   appreciate that the evoked response and non-captured artifacts are readily distinguishable during capture and non-capture for signals 200 and 202. Without limitation, a conventional peak detector may be adapted for detecting the peaks in the recorded signal received after pacing while using a 1-15 microfarad coupling capacitor having an 8 millisecond recharge time.

25   This invention has been described herein in considerable detail in order to comply with the Patent Statutes and to provide those skilled in the art with the information needed to apply the novel principles and to construct and use such specialized components as are required. However, it is to be understood that the invention can be carried out by specifically different equipment and devices, and that various modifications, both as to the

30   equipment details and operating procedures, can be accomplished without departing from the scope of the invention itself.